Colour Gradients in the Optical and Near-IR

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Abstract. For many years broadband colours have been used to obtain insight into the contents of galaxies, in particular to estimate stellar and dust content. Broadband colours are easy to obtain for large samples of objects, making them ideal for statistical studies. In this paper I use the radial distribution of the colours in galaxies, which gives more insight into the local processes driving the global colour differences than integrated colours. Almost all galaxies in my sample of 86 face-on galaxies become systematically bluer with increasing radius. The radial photometry is compared to new dust extinction models and stellar population synthesis models. This comparison shows that the colour gradients in face-on galaxies are best explained by age and metallicity gradients in the stellar populations and that dust reddening plays a minor role. The colour gradients imply M/L gradients, making the 'missing light' problem as derived from rotation curve fitting even worse.

1 The colour gradients

A sample of 86 spiral galaxies was imaged in the B, V, R, I, H and K passbands to study light and colour distributions as a function of radius. Full details of sample selection and data reduction are described in de Jong & van der Kruit (1994). The galaxies were selected to be face-on and to have a diameter of at least $2'$. The sample is statistically complete and can be corrected for selection effects. It can therefore be used to analyze the nature of the Freeman law (Freeman 1970) and this analysis has been reported elsewhere (de Jong 1995a, 1995b).

The luminosity profiles were determined in the usual way by measuring the average surface brightness on annuli of increasing radius. Radial colour profiles were created by combining profiles in different passbands. The run of colour as function of radius is put on a common scale for all galaxies in Fig. 1, where the average B–K colour at each radius is plotted as function of the average R surface brightness at this radius.
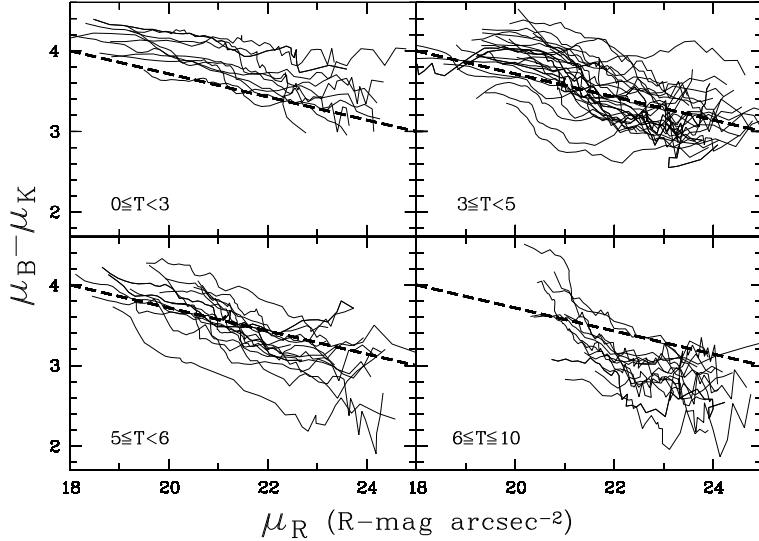
Fig. 1. The average B–K colour at each radius as function of the average R surface brightness at this radius. The galaxies are divided into 4 morphological RC3 T-type bins. The dashed lines are provided to have a common reference among the bins.

Two observations can readily be made from this diagram. Firstly, all galaxies become bluer going radially outward, correlating strongly with the average surface brightness at each radius. Secondly, even at the same surface brightness, late type spiral galaxies are bluer than earlier types (use the dashed lines to guide the eye). Furthermore it should be noted that there is a smooth transition in colour from the bulge to the disk region. The colours of bulges are nearly identical to the colours of inner disk regions (see also Peletier, these proceedings).

2   The dust and stellar population synthesis models

A possible explanation for the colour gradients is reddening due to dust extinction. As galaxies are intricate mixtures of stars and dust, we cannot describe the reddening by a simple extinction law, but have to calculate the separate contributions of absorption and scattering. To predict reddening profiles due to absorption and scattering full 3D Monte Carlo simulations were made (de Jong 1995a) of galaxies with smooth exponential dust and stellar distributions in both radial and vertical directions. The main free parameters are the dust to stellar scaleheight (z_d/z_s) and scalelength (h_d/h_s) ratios, the central optical depth $(\tau_{0,V})$ and the properties of the dust particles. The (poorly determined) Galactic dust properties were assumed, since extragalactic albedo and phase scattering functions have never been measured.
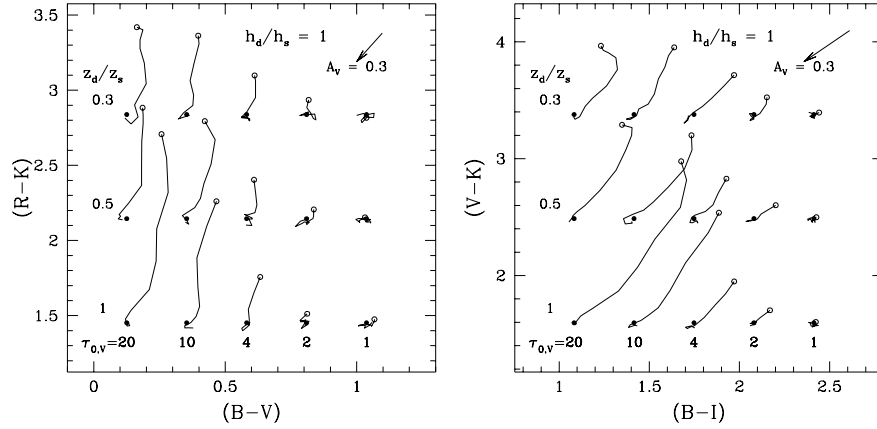
Fig. 2. The radial colour-colour reddening profiles resulting from the Monte Carlo simulations of stars and dust in exponential disks for different z_d/z_s and $\tau_{0,V}$ values. The arbitrary unreddened colours are indicated with filled circles for each model, the galaxy centres indicated by open circles.

Figure 2 shows a number of model colour-colour reddening profiles for different z_d/z_s and $\tau_{0,V}$ values. The positions of the models in the diagram are arbitrary (depending on the colours of the underlying population), but the shape of the reddening profiles are determined by the distribution and the properties of the dust. Note that all reddening profiles point in about the same direction, independent of the dust configuration, and that this direction is different from the standard screen model extinction vector (arrow).

I have used two sets of stellar population synthesis models in the comparison with the data. The Solar metallicity models of Bruzual & Charlot (1993) are used to study the colour changes of populations due to different star formation histories. Two extreme cases are considered, a single star burst model and a constant star formation model. The colours of these populations are inspected after 8 and 17 Gyr. The models of Worthey (1994) are used to study the effects that age and metallicity have on the colours of a population.

3   The comparison between models and data

Figure 3 shows the colour-colour diagrams of the models and the galaxies, again divided into four T-type bins. Note that the *same* model should fit the data in *all* colour combinations, thus in both Figs. 3a & 3b. The thin lines represent the galaxy data; the central galaxy colours are indicated by the open circles, the lines show the run of colours as function of radius. All galaxies with type T<6 are confined to a small region in these diagrams, only the later types show a considerable larger spread.
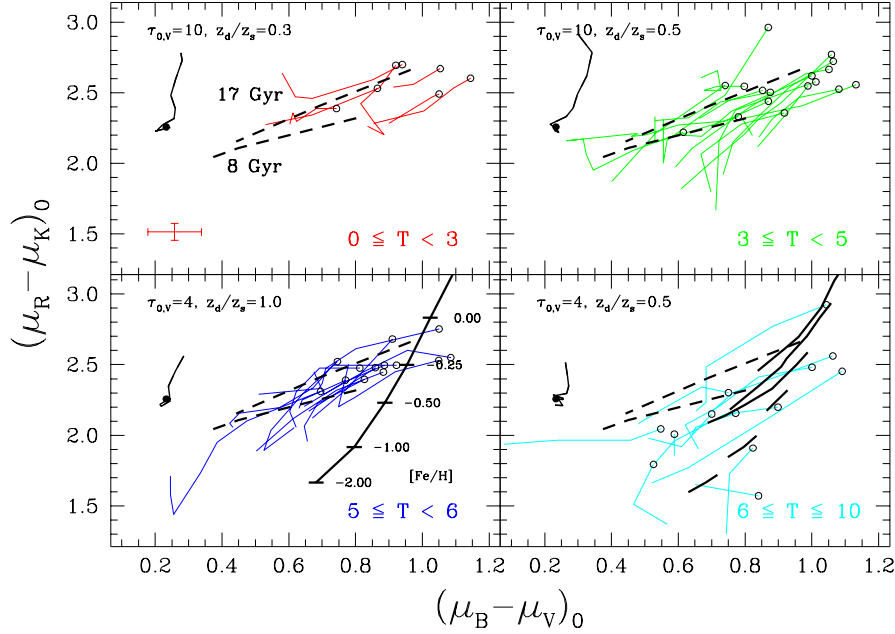
Fig. 3a. The run of B–V versus R–K colour as function of radius for the galaxies (thin lines, centre indicated by open circle). Dust models in the top left corner, Bruzual & Charlot (1993) models after 8 and 17 Gyr thick dashed lines, Worthey (1994) models for indicated metallicities thick solid lines in the two bottom panels.

Some dust model profiles are indicated in the top-left corner of the panels. As mentioned in Sect. 2, these profiles can be placed anywhere in the diagrams and their direction depends mainly on the dust properties, not on the relative distribution of dust and stars. Clearly, the colour gradients cannot be caused by reddening alone, assuming that the dust properties used are correct.

In the $5 \leq T < 6$ panels the colours predicted by Worthey's models after 12 Gyr are shown for a range of indicated metallicities. The metallicity-colour trend runs in the same direction for other ages and apparently, a metallicity gradient alone cannot explain the observed colour gradients.

The effects of different star formation histories are indicated by the two dashed lines in the centre of the panels. The red ends of these lines indicate the colours of a single burst population, the blue end of a population of constant star formation rate. Both the position and the direction of these solar metallicity models seem to agree reasonably well with the data, and the most simple explanation for the colour gradients would be age gradients across the disks of spiral galaxies. Still this cannot be the whole story, as galaxies still have star formation in their central regions, which means that a single burst is a bad approximation. Furthermore it is known from measurement of HII regions that spiral galaxies have metallicity gradients in their gas content,
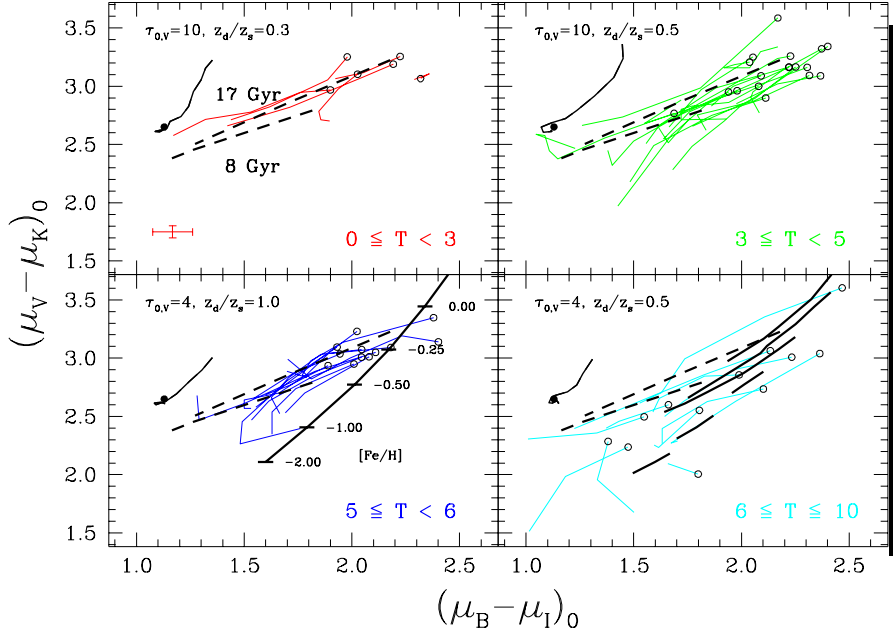
Fig. 3b. As Fig. 3a, but for B–I versus V–K.

which most likely is partly reflected in the stellar component. So the most consistent picture is one where colour gradients are caused by both age and metallicity gradients, with the central regions of galaxies being on average quite old and having a range of metallicities, whereas the outer parts are young and have low metallicities.

The large spread in colours of the late type galaxies can be explained by stellar population changes as well. The single-burst age evolution is indicated by the thick, solid lines in the $6 \leq T \leq 10$ panels, for the metallicities indicated in the $5 \leq T < 6$ panels. The colours indicate that the stellar population in some of these galaxies are on average very young and have a low metallicity.

The colour gradients imply large M/L gradients for the optical passbands, making the 'missing light' problem as derived from rotation curve fitting even worse, irrespective whether they are caused by dust or population changes.

References

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